

TELECENTRIC ZOOM LENS DESIGNED FOR THE CYGNUS X-RAY SOURCE *

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Abstract

Cygnus is a high-energy radiographic x-ray source. Three large zoom lenses have been assembled to collect images from large scintillators. A large elliptical pellicle (394×280 mm) deflects the scintillator light out of the x-ray path into an eleven-element zoom lens coupled to a CCD camera. The zoom lens and CCD must be as close as possible to the scintillator to maximize light collection. A telecentric lens design minimizes image blur from a volume source.

To maximize the resolution of objects of different sizes, the scintillator and zoom lens are translated along the x-ray axis, and the zoom lens magnification changes. Zoom magnification is also changed when different-sized recording cameras are used (50 or 62 mm square format). The LYSO scintillator measures 200×200 mm and is 5 mm thick. The scintillator produces blue light peaking at 435 nm, so special lens materials are required.

By swapping out one doublet and allowing all other lenses to be repositioned, the zoom lens can also use a CsI(Tl) scintillator that produces green light centered at 540 nm. All lenses have an anti-reflective coating for both wavelength bands. Two sets of doublets, the stop, the scintillator, and the CCD camera move during zoom operations. One doublet has $x-y$ compensation. Each zoom lens uses 60 lb of glass inside the 425 lb mechanical structure and can be used in either a vertical or horizontal orientation.

I. INTRODUCTION

The Cygnus Dual Beam Radiographic Facility [1, 2] consists of two identical radiographic sources at 2.25 MeV. Each rod-pinch x-ray source is aimed at a test object from a different angle. Each source produces a 1 mm diameter x-ray spot size, with 4 rad at 1 m, in a pulse of 50 ns FWHM. X-ray collimators define the beam axis. This radiographic facility is located in an underground tunnel test area at the Nevada National Security Site (NNSS). The sources were developed to produce high-resolution images on subcritical tests that are performed at the NNSS. Subcritical tests are single-shot, high-value events. The test objects can be different sizes and several different CCD cameras are available. So, a zoom lens design accommodating magnification changes would enhance the Cygnus facility. Three zoom lens systems are being built, with the third zoom system available to other users for future R&D work.

Figure 1 shows the anticipated layout for one of two vertically mounted zoom lens systems collecting light from a lutetium yttrium orthosilicate $\text{Lu}_x\text{Y}_{2-x}\text{SiO}_5\text{:Ce}$ (LYSO) scintillator. The test object is sealed inside a pressure vessel. Each zoom lens enclosure box is 89 inches in length and can retract away from the pressure vessel, allowing for setting the x-ray magnification at the scintillator. There are additional structures to support lead blankets (orange color). Umbilical cables carry motion

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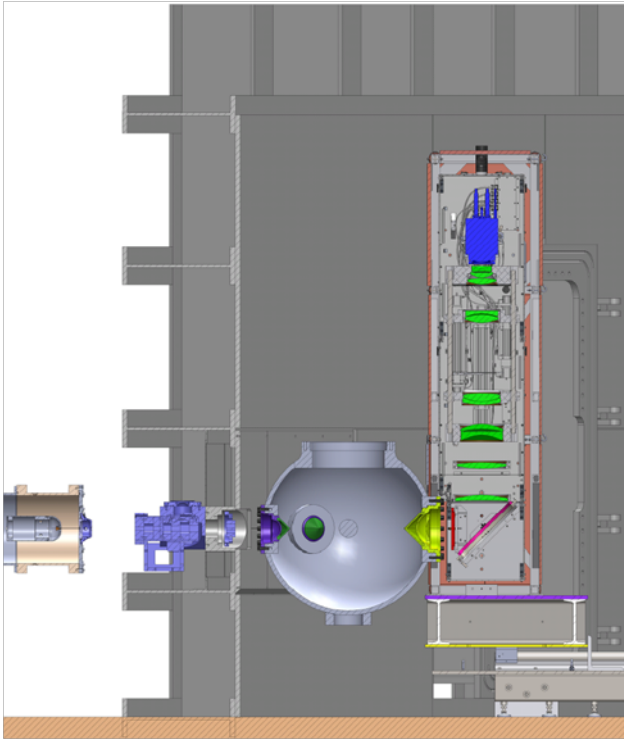


Figure 1. X-rays pass through a containment chamber which contains the test objects. Light emitted by the LYSO scintillator is sent vertically into the CCD camera.

control signals to a shielded computer work station located 20 feet away (not shown in the figure). The CCD images are sent by duplex fibers up to 100 feet away. The next sections discuss how we reached this design solution.

II. OPTICAL DESIGN PROBLEM

Light is continuously produced along each x-ray track as it passes through the scintillator. Light emission from a thick scintillator should be viewed along the x-ray track generating the light. The 1 mm x-ray point source is 2.4 m away from the scintillator, so the chief rays of the light emission should actually be diverging as they exit the scintillator. We found it difficult to collect these ray bundles, so a compromise was to make the zoom lens telecentric, meaning that the center rays of each ray bundle emanating from each field point of the scintillator must be parallel to the optical axis.

A ray trace of the LINOS lens [3] used on Cygnus prior to the new zoom design is shown in Figure 2. The LINOS lens is coupled to the same vacuum system as the CCD camera. This lens does not meet the telecentric requirement, and it has no zoom capability but works well when imaging an object plane. Because the Cygnus imaging system is starved for light, thicker scintillators are desirable. With a thick scintillator, this lens collects light at different angles to the x-ray trajectory resulting in

image blur. The LINOS lens has a fixed working distance from the scintillator to its first optical element. In this configuration light is collected from a 150 mm diameter scintillator and imaged onto a 50 mm diameter CCD camera. There is a fixed magnification for this imaging system. When using a higher-resolution CCD camera that has a 62 mm diameter, light will be collected into only 50 mm of the 62 mm diameter area available. Thus, the available resolution of the camera is not used.

In addition, larger-diameter scintillators and better resolution are desired. Another requirement is to vary the size of the test object being x-rayed. To collect the best resolution, the lens needs to zoom into smaller object sizes. When different scintillators and/or CCD cameras are used, the current LINOS lens does not collect optimal resolution from the scintillator. Currently, the CCD camera chip can be either under-filled or over-filled. Another design goal is to collect more light than the LINOS lens, which collects 0.08 NA. Generally, short-pulsed x-ray imaging is light-starved, so, more light will improve the signal-to-noise statistics of the recorded image. These peculiar combinations of requirements make this a challenging optical design problem.

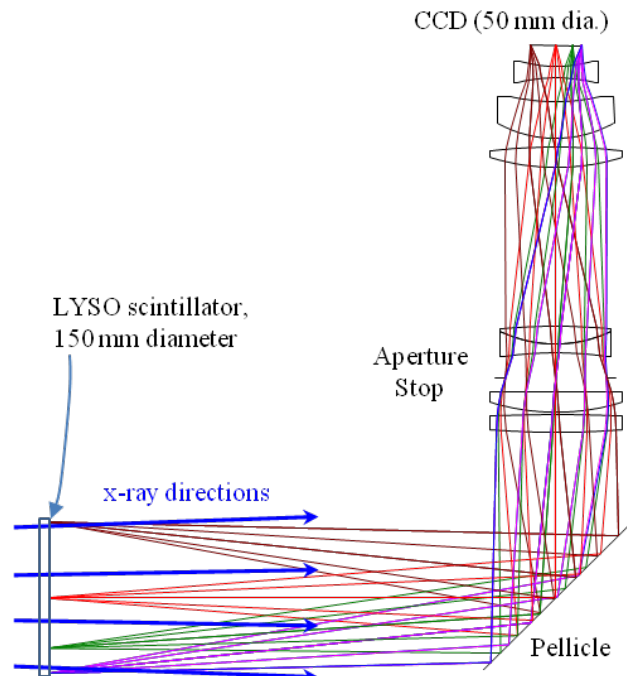


Figure 2. Imaging with the LINOS lens can only use thin scintillators because light is not collected along the x-ray axis.

III. OPTICAL DESIGN SOLUTION

We need to image light generated from a volume emitter. Our zoom lens system collects 0.1 NA light from the scintillator, which emits light with much larger NA. Baffling rejects unwanted light. Figure 3 is a layout for zoom position #1 with the actual glasses listed [4]. All

glass elements use Ohara glass. The first three elements use an Ohara version of fused silica to gather the light from the scintillator. A mechanical shutter blocks high-explosives light after x-ray event time, preventing unwanted background light during CCD readout. The elliptical pellicle is decentered by 16.5 mm to center the footprint of light reflected off its aluminum coating. The large elements allowed equal light collection efficiencies across the field of view. Notice that emission directions collected from different field points are all parallel.

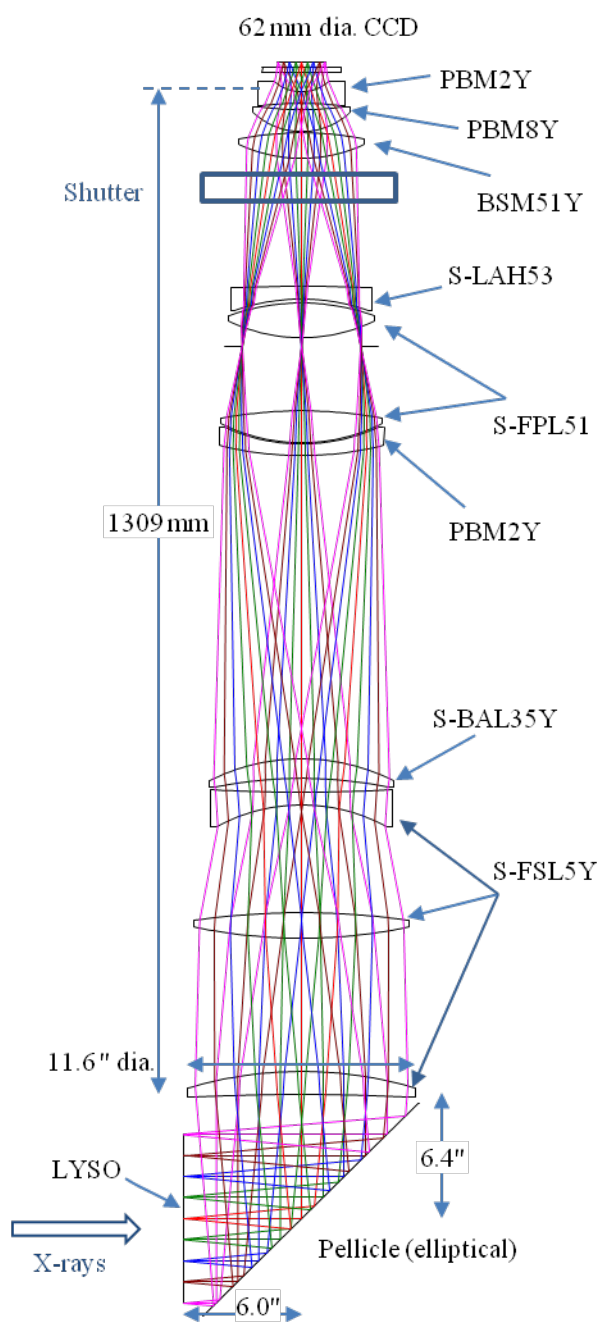


Figure 3. Glass material used for the zoom lens.

Figure 4 identifies components that move during magnification changes. The zoom lens operation is as follows: the movement of the magnifier lens group (1st moveable doublet) changes image magnification for different scintillators, and movement of the adjuster lens group (2nd moveable doublet) compensates for aberration induced by the magnification change. In this case the stop size and position are also allowed to vary. The CCD camera is allowed to refocus. The mechanical shutter does not move.

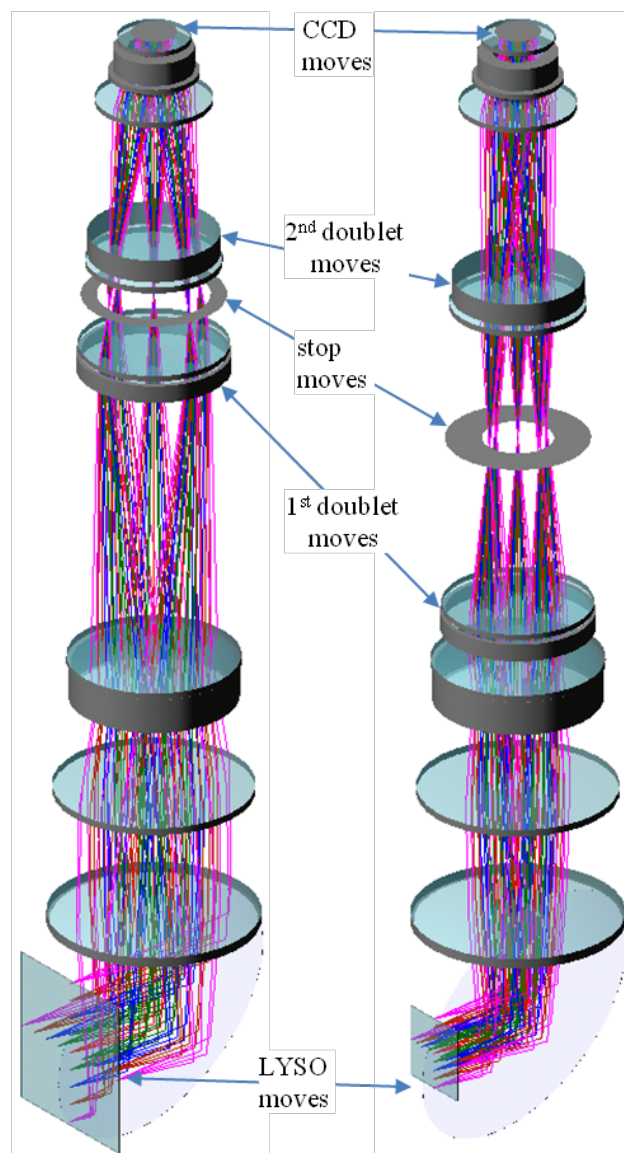


Figure 4. Changing magnifications requires five components to move along the optical axis. (Only the useful area of the scintillator is shown emitting light as the physical size of the scintillator does not change.)

Analysis of the tolerances of the zoom lens was conducted. To reduce the costs and risks of manufacturing these large lenses, the thickness tolerance was relaxed to

± 2.0 mm. In order to achieve best resolution, the second moveable doublet needs to be capable of a manual XY adjustment of only ± 1.0 mm. But, without this small adjustment, which compensates for lens manufacturing errors, some of the zoomed positions have close to zero modulation transfer function at 16 lp/mm. Because of the large thickness tolerance value, most of the lenses arrived at the thickest value. The air spaces were re-optimized after the lens elements were received. Figure 5 shows compensator value ranges.

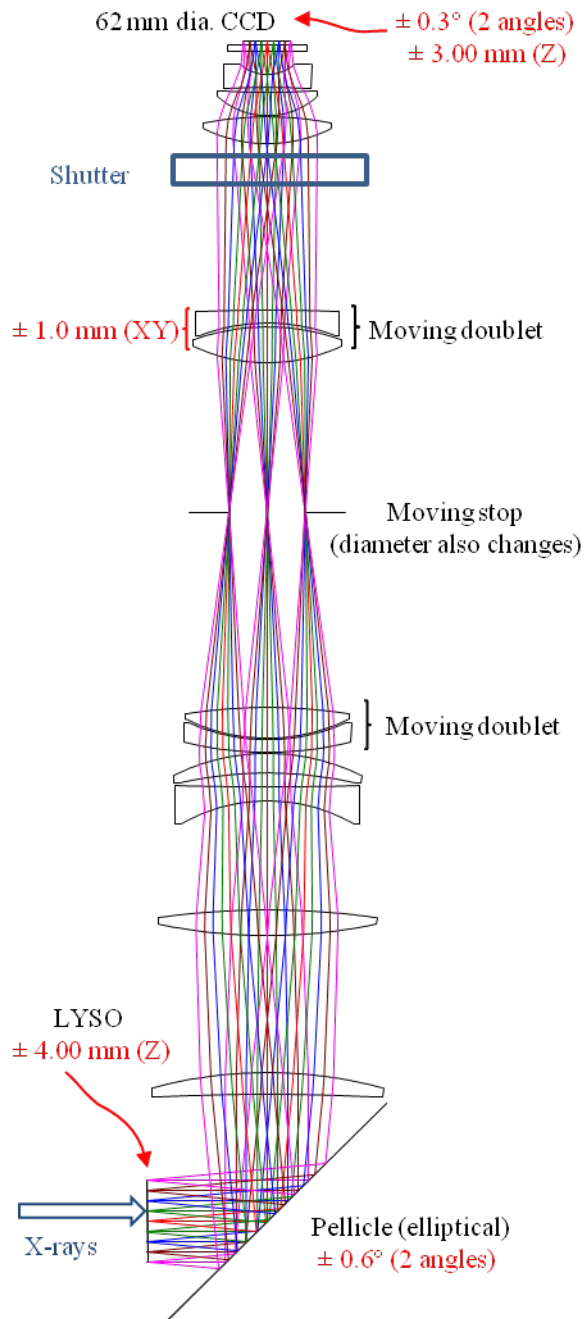


Figure 5. Compensators used to control manufacturing and assembly errors.

The elliptical pellicle will be mounted into a tip/tilt frame. Specification for the pellicle surface irregularity was 5λ over any 4-inch subaperture, measured at 633 nm. Figure 6 shows a CAD model of how the pellicle is positioned between the scintillator and the first lens element. The scintillator also has tip/tilt adjustment mechanisms. The first lens does not tilt. The pellicle is oversized to minimize edge effects of the bounding of the aluminized Mylar to its frame. The pellicle mount is pinned to the base plate for removal and repositioning. Because there is no metal behind the pellicle, x-rays have no opportunity to scatter off it.

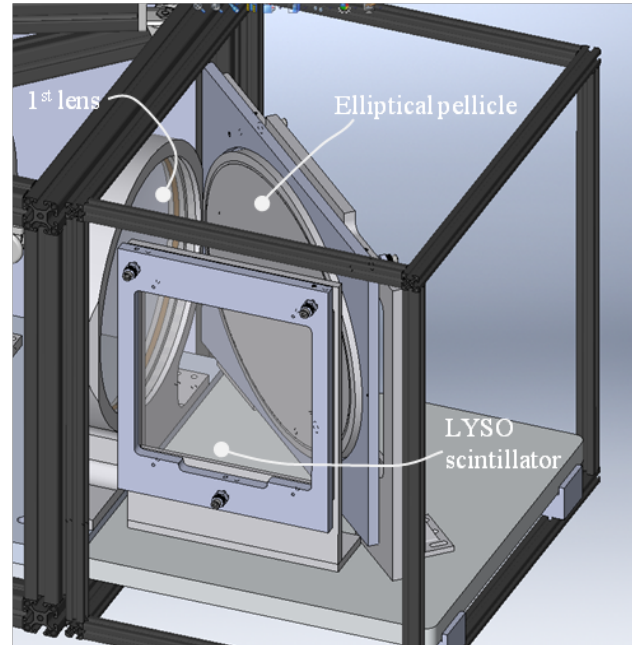


Figure 6. Both the pellicle and the scintillator will have manual tip/tilt adjustments for alignment.

Stray light analysis (not shown here) will reveal where the unwanted light from the scintillator is blocked. Computer-controlled rail systems transport moveable components, as shown in Figure 7. The CCD camera is mounted into a custom gimbal that has manual tip/tilt adjustments and clocking. It also is mounted to a rail for focus adjustments. Both the pellicle and the scintillator have manual tip/tilt adjustment mechanisms.

The rail systems for moving the optical components make use of an absolute encoder that does not require electrical power to maintain its value. The environmental use of this zoom lens system has to allow 20° temperature difference between winter and summer operations. The rail brakes used to release movement of optical components require electrical power, and they are normally powered off.



Figure 7. The first zoom lens assembly.

IV. CHANGING FROM A BLUE TO GREEN SCINTILLATOR

A thallium-activated cesium iodide CsI(Tl) scintillator emits with green wavelengths and has a broad spectral range of 400–725 nm with a peak at 550 nm. The LYSO has a peak emission at 435 nm. The current optical design has poor resolution when changing the spectrum from blue to green. We systematically varied only one lens glass material at a time to see which element was the most sensitive for correcting resolution. We then systematically selected a second lens glass material to see if more improvements could be found. The result was that only one lens element needed its glass material changed.

In order to accommodate future uses for this zoom lens, all optical elements are anti-reflection coated for 390–700 nm wavelengths, with the peak transmission at 500 nm. Figure 8 shows zoom lens system modifications that will allow operation at green wavelengths; only one glass element has to be exchanged to accommodate operating in the green wavelength. The lens material will be changed from S-LAH53 to S-LAM55. The positions of all lens elements have to shift, as shown in the figure. This will require another base plate to be fabricated with holes for either blue or green operation. The third zoom lens system we build will probably operate with this green scintillator.

V. CONCLUSION

Improvements over the previous Cygnus imaging system were made. Telecentric light is gathered from a volume emitter. The lens/camera system can be translated along a rail to get different x-ray magnifications at the scintillator. The zoom lens allows for optical magnification in the range of 0.23 to 0.59. The zoom lens gathers 56% more light than the LINOS lens with 2× better resolution. No vacuum system is required for the zoom lens. In the future, we will be able to use either the LYSO or a CsI(Tl) scintillator.

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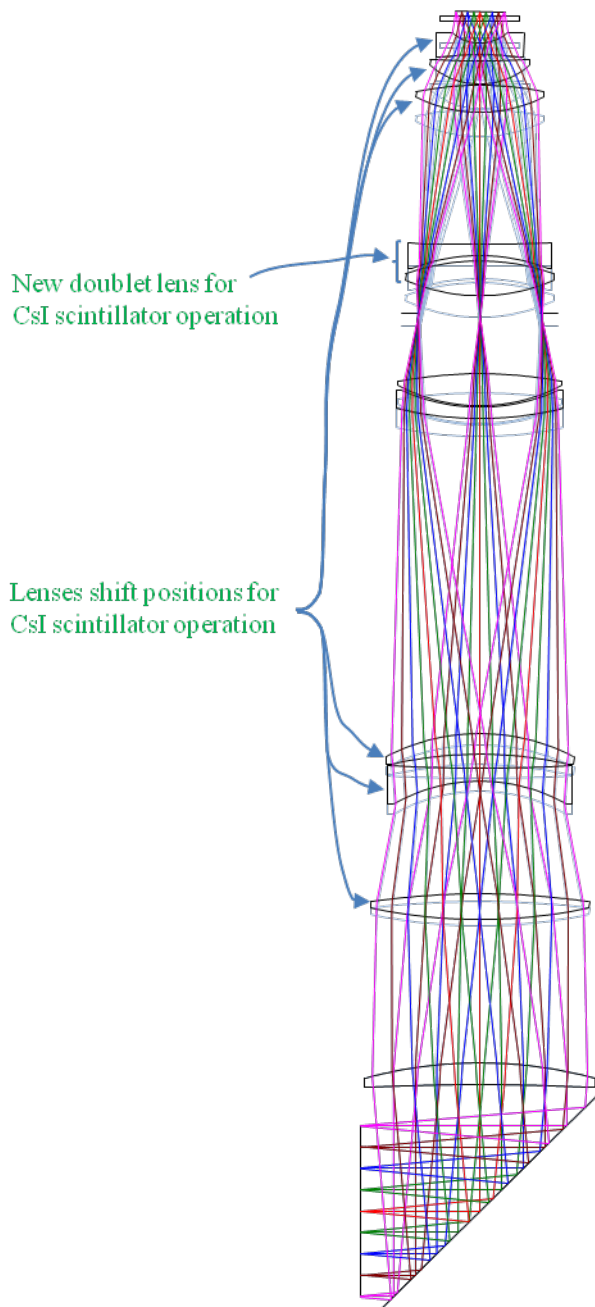


Figure 8. By shifting the position of six lenses and replacing one lens element, the zoom lens system can operate with a CsI(Tl) scintillator.